COMPACT, LIGHT WEIGHT MECHANISMS FOR HIGH PRECISION MICRO-MANIPULATORS

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ABSTRACT

This paper presents innovative concepts developed at the "Institut de systèmes robotiques" for the realisation of high precision micro-manipulators.
Our approach allows to design compact, light and reliable mechanisms. Piezoceramic micro-actuators, flexible bearings and end-effectors in shape memory alloys are descibed and illustrated with several prototypes.
The proposed concepts satify remarkably well the in-flight space experiments requirements and are believed to be excellent candidates to be used in embarked "Microlabs".

1. INTRODUCTION

Since the beginning of the nineties, the industry of Microsystems asks for a miniaturization of the production tools (i.e. machines and production facilities), the goal being to reduce weight, volume and power consumption and finally, to reduce the production costs. At the same time, immunity of the systems against environmental perturbations, such as vibrations or temperature fluctuations is improved. In the academic community, this concept is generally called miniature-factory or "Microfactory". It refers to a set of cooperating machines in a tabletop containment to produce, process and manipulate micro-devices [1].
The Microfactory characteristics satisfy remarkably well the in-flight space experiment requirements and could soundly be used to realize embarked "Microlabs".
This paper describes innovative approaches for the design of actuators, mechanical structures and end-effectors, all dedicated to Microfactories or Microlabs. The proposed solutions are simple and highly reliable. Our approach is illustrated in this paper with several examples.

2. PIEZOCERAMIC MICRO-ACTUATORS

In the frame of the Microlab concept, "stick and slip actuators" are characterized by their remarkable simplicity. Without any precision mechanical parts, nor delicate assembly processes, and using low cost material, we can design micro-manipulators with nanometer resolutions and large wokspaces (several cubic centimeters) [2].

2.1 Operating principle

An inertial mass (slider) is supported and guided by deformable legs (figure 1). Two modes of operation are defined, viz. stepping- and scanning-modes.
In the stepping-mode, each step consists of a slow deformation of the legs followed by an abrupt jump backward. During the slow deformation the mass follows the legs because of friction (stick), whereas it cannot follow the sudden jump because of its inertia (slip).
The stepping mode allows long displacements at a relatively high speed (typically 5 mm/s). The resolution is limited to a step or so (200 nm).
Once the position is within less than a step distance of the target, the legs are deformed slowly until the final position is reached. In this mode, called scanning-mode, the resolution is a fraction of a step (typically better than 5 nm).

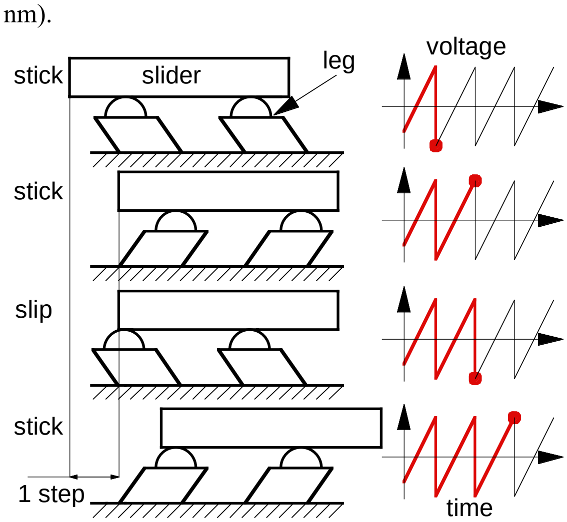

Figure 1: Stick and Slip Actuator, operation principle

2.2 Experimental results and performances

A controller has been implemented and the performances of the 1-DOF actuator is shown on figure 2 [3].

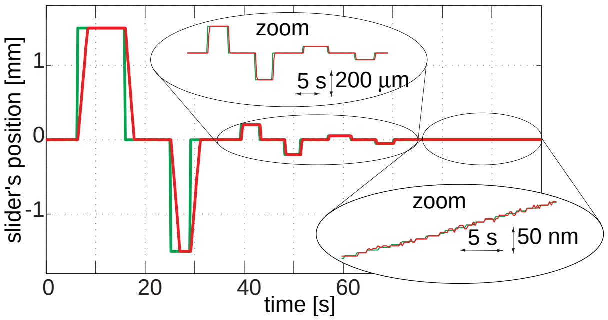

Figure 2: Illustration of the remarkable dynamic properties of these actuators (from nanometers to millimeters). Actually, the accuracy of the system is limited to 5 nm by the resolution of the position sensor (interferometer).

2.3 Prototypes

Several micro-manipulators using Stick and Slip Actuators have been developed and tested at ISR. Some of them are integrated in micro-assembly or micro-telemanipulation systems.

Simplicity, rigidity, high resolution and easiness of integration into a system are the main features we have considered during the development of our micro-manipulation systems.

2.3.1 A six degrees-of-freedom platform

Stick and Slip Actuators can easily be integrated into complex mechanical structures. Figure 3 shows a parallel kinematics actuated by three Stick and Slip Actuators, each of them having 2-DOF. The platform has thus 6-DOF (3 translations and 3 rotations).

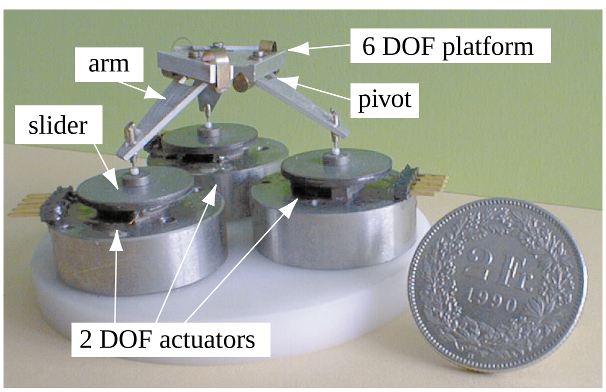

Figure 3: 6 degrees-of-freedom platform.

Its workspace is evaluated at about 140 mm^3, for an overall volume of the structure smaller than 4 cm^3. The maximum payload is 0.1 N [4].

Such platform could be used, for example, to position and orientate samples under a microscope.

2.3.2 A three degrees-of-freedom mobile micro-robot

An innovative concept, named “Monolithic Piezoceramics Flexible Structures”, has been invented at ISR allowing to design extremely simple mobile micro-robots [5].

Figure 4 shows a picture and exploded view of a 3-DOF mobile micro-robot composed of only 6 simple mechanical parts.

These micro-robots have a resolution of a few nanometers and a maximum speed as high as 3 mm/s. Their workspaces are limited only by the table on which they are moving (and the length of the wires). A permanent magnet allows them to work also upside down.

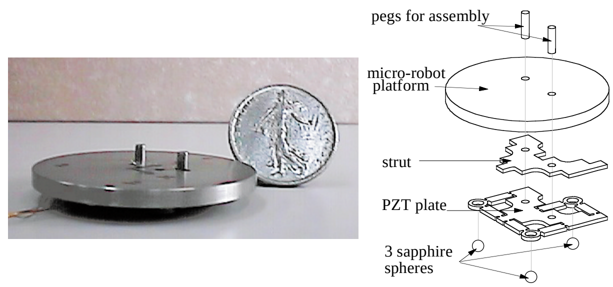

Figure 4: A 3 degrees-of-freedom mobile micro-robot.

2.4 A few examples of application

A similar micro-robot was used to carry a micro-electrode and make **micro-EDM machining**. A vertical axis was added to obtain the fourth degree-of-freedom required by this application. Die-sinking and milling experiments, without rotation of the electrode, were done on cover glass in automatic and manual modes. Typical milling speeds were 0.5 mm/s [6].

Replacing the electrode by a micro-gripper, the robot was used in an experimental setup for **micro-assembly** (figure 5). The goal was to insert the rotor of an electrostatic motor into its stator. The clearance was 2 µm. The diameter of the rotor was 250 µm for a thickness of 150 µm. The micro-robot is placed under an optical microscope. A 3-D vision system provides a position feedback with submicron accuracy. The system successfully completed the insertion operation in automatic and manual modes [7].

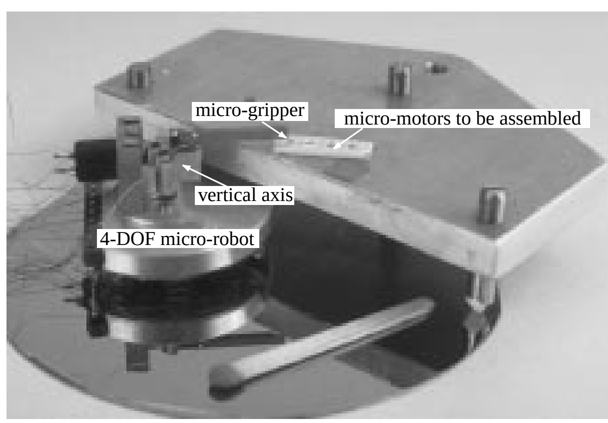

Figure 5: Micro-assembly system.

Finally a micro-telemanipulation system for biological specimens was developed. The micro-manipulator can carry micro-tools such as micro-electrodes or micro-pipettes to operate with a nanometr accuracy on biological tissues or cells [8].

3. MONOLITHIC FLEXIBLE MECHANICAL STRUCTURES

In many cases an inappropriate mechanical structure for a manipulator can be an insurmountable limiting factor to its precision. For example backlash or friction can hardly be overcome by sensors or controllers. An efficient approach to this problem is to use a new concept of structures specially dedicated to high precision micro-manipulators. It consists in replacing the traditional rolling or plain bearings by flexible bearings. We present here the advantages of flexures compared to traditional bearings then we show some examples of original flexures and a 3 degrees-of-freedom high precision micro-manipulator.

Like plain or rolling bearings, flexures are joints connecting solid members and permitting relative motion in some directions while constraining motion in others. But whereas the two former types of bearings rely upon the friction or rolling of solid bodies on each other, flexures use the elastic properties of matter. This brings numerous advantages for high precision mechanisms [9]:

- Absence of friction : plain or rolling contact between solids inevitably generates friction which alters the joint's functioning. Friction dissipates energy, provoking mechanical hysteresis. At low speed it causes halting motion due to the "stick & slip" phenomenon which limits the resolution of the movements. Finally friction is at the origin of wear. Flexure are free from all solid friction. Solely remains the internal friction of matter which is practically negligible.
- Absence of wear : wear reduces the precision of plain and rolling bearings because it alters their geometry and increases their mechanical play. Moreover, it is the principal factor limiting their life-time. Flexures do not suffer from these drawbacks and have their life-time limited only by the eventual fatigue of the material. Good design maintaining the stresses below the fatigue limit allow to guarantee almost infinite life-times.
- Absence of mechanical play : to reach high precision, plain and rolling bearings often require complicated play compensation. Per definition, flexures have no play.
- High rigidities : the more rigid the mechanical structures of machines, the more precise they are statically (when external loads are applied) and dynamically (when vibrations occur). The rigidity of rolling bearings depend on the pressure of rolling elements on top of a rolling surface. With small bearings, the small radiuses of the rolling elements limits the rigidity. Well designed flexures can be much more rigid than rolling bearings.
- Compact and monolithic structures : plain and rolling bearings are made of many mechanical parts which are assembled. This assembly increases their bulkiness and reduces their construction precision. Wire-electrodischarge machining allows to manufacture very complex flexible structures monolithically, hence very compact and precise.
- Immunity to contamination : the wear and required lubrication of plain and rolling bearings frees particles of matter which can pollute the air of clean rooms. On the contrary, when used in dirty environments, dust can easily perturb or even block these bearings. Flexures are perfectly clean and are not affected by dirt.

The main limitation of flexures is their range of motion which must be restricted to avoid intolerable stresses inside the material. This calls for flexible parts with ever thinner cross-sections. Wire-electrodischarge machining allows to manufactures flexible parts having thicknesses of a few tens of microns with relatively long motion ranges. Much work is done to establish efficient models to predict the behavior of such thin flexures [10].

3.1 Examples of flexures

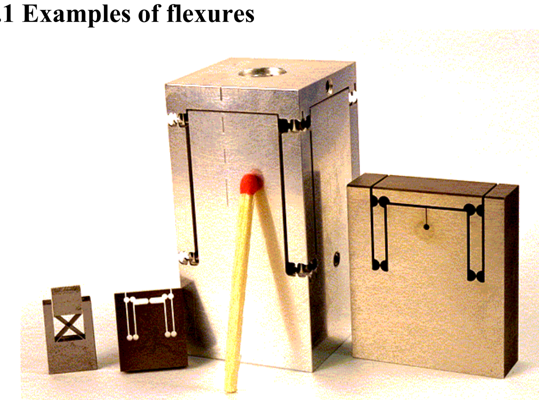

Figure 6: Examples of monolithic flexures. From left to right : cross spring pivot (tempered steel); linear stage with 4 necked down flexures 25µm in thickness and a motion range of 0.5mm (tempered steel), X Y θZ stage (Perunal Aluminum alloy), linear stage. The match is 50mm long.

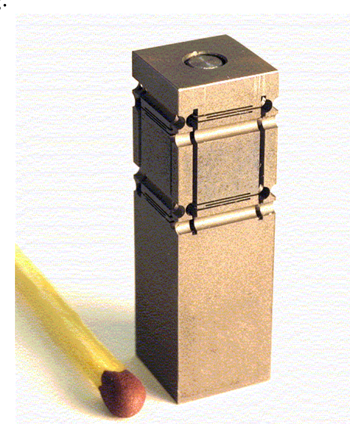

Figure 7: Compact monolithic XY stage with integrated flexible bellow (tempered steel). The flexible parts are 25µm in thickness, the motion range is 0.5mm. The part is 30mm in height.

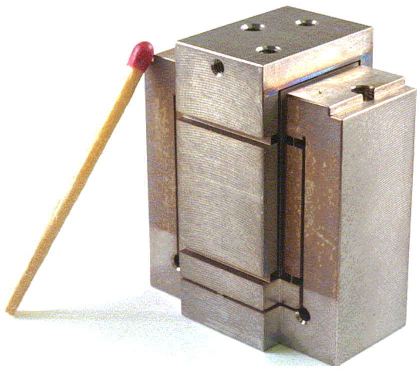

Figure 8: Compact monolithic serial XY stage. Motion range : ±1mm; thickness of flexible parts: 60µm; material: titanium alloy TiAl6V4. The match is 50mm long.

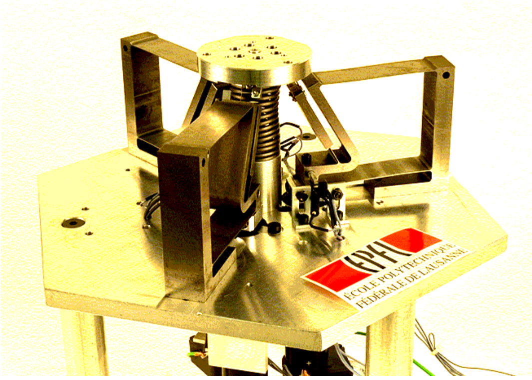

Figure 9: Orion X-Y-Z robot. This parallel robot is composed of three monolithic arms (tempered steel) connected to the moving platform on top. Each arm is actuated by a screw-nut system and a DC motor with encoder. The resolution of each axis is better than 0.8µm. The linear motion range of the robot is ±5mm, the angular motion range is ±7°. (The EPFL sticker is 60mm long).

4. SHAPE MEMORY ALLOYS END-EFFECTORS

Shape Memory alloys (SMA) provide a simple, compact, lightweight, lubricant-less and shock-less solution in the field of actuator for space engineering. They have been successfully introduced in several space applications like for deployment structures (Rapana truss on the orbital station MIR) [11], releasing mechanisms (solar panels on Clementine spacecraft) [12] as well as small actuators (Material Adhesion Experiment on Mars pathfinder) [13]. Moreover, among all actuators, Shape Memory Alloys have the best force/weight ratio in the micron scale world. They can deliver a very large force in a narrow space, which makes these alloys attractive for micro-engineering applications. Until today, most of SMA micro-systems use only the SMA as the actuator combined with others mechanical parts like pullback springs, guiding systems, etc. All these systems are not suitable for very small applications (dimensions less than a few millimeters) because of the assembly of microelements and in some cases, the friction between mechanical elements.

A new concept of monolithic SMA mechanism has been developed in our laboratory. This concept consists in considering the SMA not only as a part of a mechanism *but as a mechanism in itself* [14]. In the case of a microgripper, the actuator, the jaws and the pullback spring are all included within the *same piece* of material. This allows us to create versatile, simple, easy-to-assemble, sub-millimeter and powerful microgripper.

A first design was developed in the framework of an industrial project where the goal was to develop and automatize the assembly of micro-endoscopes. The challenge was to carefully manipulate small cylindrical micro-lenses with diameters of 0.25 to 0.35 millimeters.

A first prototype of microgripper consists of a small piece of one-square millimeter SMA material (NiTiCu). The gripper has one moving arm, which closes on heating and opens on cooling. The reversible motion is done by using the so-called, Two-Way-Shape-Memory-Effect (TWSME). This effect appears when the material is submitted to a training process, which consists in a constrained thermal cycling of the material.

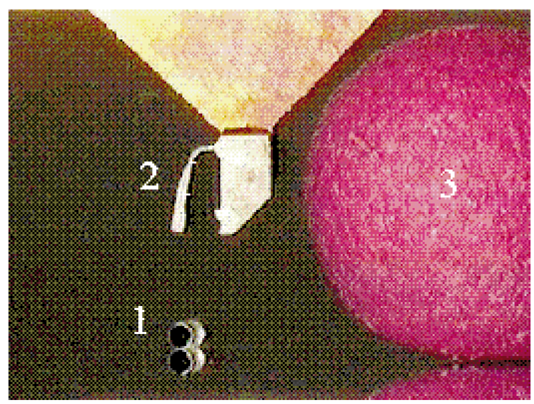

Figure 10 : The Two-Way-Shape Memory micro-gripper 1.Grin lens (on a glass support); 2. Micro-gripper ; 3. A match.

The main characteristics are:
- Maximum grasping force: 16 mN
- Weigth: < 1 mg
- Size: around 1 mm^2
- Thickness: 0.17 mm
- Material: NiTiCu
- Machined by laser
- Power consumption: around 0.4 W*
- Activation temperature: 60 to 80°C*

* Depends on the SMA material used.

The gripper has been tested for 200'000 cycles of lenses grasping (the fatigue characteristic shows saturation after 200'000 cycles).

The main advantage of this device is the simplicity of fabrication and actuation. It can be used in special environments like clean-rooms, vacuum or zero gravity.

5. CONCLUSION

The increasing number of experiments run in micro-gravity will necessary lead to the development of a new kind of laboratory equipment dedicated to space.

The ISR does not have any experience in this field yet, nevertehless, the microfactory concepts presented in this paper have many similarities with the space requirements :

- small weigh and dimensions;
- low energy consumption;
- work in vacuum or controlled atmospheres;
- handling strategies for micro-parts adapted to micro-gravity;
- immunity to chocks and vibrations.

Hence we believe that these new design approaches can be of great use for the realization of Microlabs to be embarked in space.

6. AKNOWLEDGMENT

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